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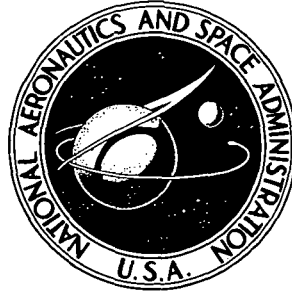
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ADHESION, FRICTION, AND WEAR OF A COPPER BICRYSTAL WITH (111) AND (210) GRAINS

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16. Abstract

Sliding friction experiments were conducted in air with polycrystalline copper and ruby riders sliding against a copper bicrystal. Friction coefficient was measured across the bicrystal surface and the initiation of adhesive wear was examined with scanning electron microscopy. Results indicate a marked increase in friction coefficient as the copper rider crossed the grain boundary from the (111) plane to the (210) plane of the bicrystal. Adhesion, friction, and the initiation of adhesive wear was notably different in the adjacent grains of differing orientation. A slip-band adhesion-generated fracture mechanism for wear particle formation is proposed.

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SUMMARY

Sliding friction experiments were conducted in this investigation with both polycrystalline copper and ruby riders sliding against a copper bicrystal surface in air. The riders had a 1.5-millimeter radius and were loaded against the bicrystal surface with loads of 50, 100, and 200 grams. The sliding speed of the friction experiments was 1.4 millimeters per minute. The scanning electron microscope was used to examine the wear scars on the specimen surfaces after sliding. Only a single pass was made across the bicrystal surface.

The results of the study indicate that marked changes in friction coefficient occur in sliding across a grain boundary. Friction coefficient was higher for the (210) plane than for the (111) plane. A distinct change in friction was observed at the grain boundary. While adhesion occurs in sliding across both grains, the amount of surface distress differs. The initiation of the formation of adhesion wear particles with the copper bicrystal appears to be by fracture along slip bands.

INTRODUCTION

In most practical lubrication systems, metals and alloys are used in their polycrystalline form. The friction behavior of metals is known to be anisotropic from single-crystal studies (refs. 1 to 4). Thus, it might be anticipated that, in lubrication systems where large grained structures are used, variation in grain orientation could influence friction. Although the influence of orientation on friction has been studied, the effect of the grain boundary on this same property has not.

Grain boundaries have been shown to influence the physical and mechanical behavior of metals. Examples of some properties they influence are (1) surface energy (ref. 5), (2) dislocation behavior (ref. 6), (3) fracture (ref. 7), and (4) diffusion (ref. 8). In

general, the energy of the grain boundary is higher than an adjacent grain, which may result in increased adhesion. Dislocations in grains adjacent to a grain boundary will be impeded in their motion by the boundary, and fracture can occur intergranularly. Diffusion occurs more rapidly along a boundary, and this can influence surface activity and, in turn, adhesion and fixation.

The objective of this investigation was to determine the influence of a grain boundary in a copper bicrystal on friction behavior. Further, the initiation of adhesive wear in the adjacent grains was examined with scanning electron microscopy. Hemispherical copper and ruby riders slid across the copper bicrystal surface. The hemisphere had a radius of 1.5 millimeter and was loaded against the disk surface with loads of 50, 100, and 200 grams. The sliding speed was 1.4 millimeters per minute. All experiments were dry sliding in air.

MATERIALS

The copper bicrystal and the copper rider specimen used in this study were prepared from 99.999 percent copper. The bicrystal was prepared from a single crystal by stressing to cause recrystallization and then heated to promote grain growth. Surfaces were polished with metallurgical papers down to 600 grit. They were then electropolished in phosphoric acid. Just before use the surface film left after electropolishing was removed with levigated alumina on a soft polishing cloth.

The bicrystal was oriented using the conventional Laue technique. One of the two grains was within 4° of the (111) orientation. The second grain was within 2^O of the (210) orientation. Thus, the included grain boundary was a high angle boundary of 39°. The ruby slider had a radius of 1.5 millimeters and was cleaned before running with moist levigated alumina.

APPARATUS AND PROCEDURE

The apparatus used in this investigation is shown schematically in figure 1. The apparatus consisted basically of a microscratch hardness tester to which a drive motor with a gear reduction head was attached to provide uniform motion, at various speeds, of the bicrystal surface under examination. In this study a constant speed of 1.4 millimeters per minute was used.

The copper or ruby rider was mounted in an arm above the bicrystal surface. Loading was accomplished by the application of dead weights directly over the rider. The arm retaining the rider had a strain-gage assembly for monitoring frictional force. A newly prepared slider was used for each run.

2

All experiments consisted of a single pass across the crystal surface. Friction force was continuously monitored during sliding. All experiments reported herein were conducted in air.

Following running, the specimens were examined by scanning electron microscopy. All micrographs were taken at a tilt angle of 45° with the tilt axis being horizontal on the micrographs. The magnifications given are all nominal.

RESULTS AND DISCUSSION

Sliding friction experiments were conducted with a polycrystalline copper rider sliding across the copper bicrystal surface in air under a load of 100 grams. The actual friction traces obtained are presented in figure 2. In figure 2(a) sliding was from the (210) grain to the (111) oriented grain. In figure 2(b) the sliding proceeded in the opposite direction. Sliding was initiated on the (111) oriented grain, across the grain boundary and onto the (210) oriented grain.

Figure 2 indicates that a difference in friction behavior exists in the grain boundary region. This is particularly evident from figure 2(b) where a very marked increase in friction coefficient is observed in the region of the grain boundary. As is evident from figure 2 the friction coefficient changes more drastically when the copper slider approaches the grain boundary from the high atomic density, low surface energy (111) grain. The grain boundary between the adjacent grains of the copper bicrystal is a high angle boundary (39°). The grain boundary energy for this degree of atomic mismatch is near the maximum achievable in copper (ref. 5).

In addition to a change in friction coefficient in the region of the grain boundary, friction coefficients were distinctly different on adjacent grains. Friction coefficient was less for the (111) grain than it was for the (210) grain. These results are in agreement with earlier observations (ref. 1).

In addition to differences in the coefficient of friction on the two copper grains of the bicrystal, there were also notable differences in surface topography. The track generated on the two grains can be seen in the scanning photomicrographs of figure 3. Figure 3(a) is of the (111) grain, and 3(b) of the (210) grain.

It is of interest to note in figure 3 the difference in the width of the tracks generated on the differently oriented grains. The track generated on the (210) surface is nearly twice the width of that on the (111) surface. These tracks were the result of a single pass across the surface.

A close examination of the (210) surface micrograph indicates the presence of surface fracture cracks. The same general type of cracks occurred in the narrow track on the (111) surface, but they were smaller. The cracks in both grains are shown at a higher magnification in figure 4. In the crack of figure 4(b) copper appears to have

adhered to the passing rider and been lifted upward following the horizontal motion; that is, adhesion occurred to the rider. As the rider continued to move relative to the disk, adhesive bonds across the interface were sufficiently strong to pull metal up from the surface. The cross sectional area of material being lifted or peeled continued to increase with tangential motion until the interfacial adhesion between the rider and bicrystal bonding was weaker than the fracture strength of the bulk of the bicrystal in the area of contact and separation of the rider and bicrystal occurred.

The very significant aspect of the fracture cracks developed in the metal surface is that they occurred along crystallographic slip planes. In figure 4 the base of the crack to the point where it appears at the surface is very smooth, which indicates, in fact, that fracture occurred along slip bands in the metal. Tensile fracture cracks occurred in a number of areas along the track. In each and every case the crack wall was smooth, which indicates fracture along slip bands.

The marked difference in surface distress for the two grains prompted experiments in which sliding was restricted to a single grain. After sliding equal distances on the two grains, rider wear scars were compared. There was not only a difference in the size but also in the texture of the rider wear scar as indicated in figure 5. Figure 5(a) is the scar generated on the (111) surface, while that of figure 5(b) resulted from sliding contact with the (210) surface. The scar generated by sliding on the (111) surface is very smooth compared with that generated by sliding on (210) where appreciably metallic transfer due to adhesion was observed. Thus, the orientation of the copper grains not only affected the nature of the track generated on the grain itself but also the degree and nature of the scarring that occurred to the surface of the polycrystalline rider.

In order to explore the effect of mechanical parameters such as load on the grain boundary friction behavior of the copper bicrystal, experiments were conducted at loads of 50 and 200 grams, for comparison with 100-gram load results. The purpose was to determine if the effects seen in figure 2 still persisted at loads less than and greater than 100 grams. The results of these experiments are presented in the actual friction traces of figure 6.

Examination of the results of figure 6 indicates that, just as with a 100-gram load, friction differences are observed in the grain boundary region at both 50 and 200 grams. Further, as was observed in figure 2, friction was less on the (111) plane than on the (210) plane surface.

Even at the relatively modest 50-gram load, fracture cracks developed along the length of the track. Some of these are shown in the scanning electron photomicrographs of figure 7. The micrographs show that the copper appears to have broken up into platelets leaving behind a series of smooth fracture crack walls. The appearance of the crack is similar to that at 100 grams; load crack formation appears, therefore, to be slip band initiated.

4

Slip bands are evident in the micrographs that were taken of the experiments conducted at the 200-gram load (fig. 8). Note again the layered structure of the copper above the crack. It is proposed that these projections above the specimen surface may serve as the source of wear particles with additional passes across the surface. This point will be discussed later.

In order to establish that adhesion was playing a dominant role in the generation of the fracture cracks, sliding friction experiments were conducted with a ruby rider sliding across the copper bicrystal surface. Although the adhesion of copper to aluminum oxide can occur, it is much less likely than that of copper to copper. Scanning electron micrographs of the tracks generated by the ruby sliding on the copper bicrystal are presented in figure 9. An examination of figure 9 indicates a complete absence of fracture cracks such as those observed with a copper rider in figure 3. The distinct differences in friction coefficient observed in figures 2 and 6 with copper riders and a change in surface grain orientation were not observed when a ruby rider was used. The friction for the ruby rider sliding on the bicrystal was approximately 0.2 for both grains.

Surface profile traces were made of the tracks of figure 9 and these are presented in figure 10. There is not a really notable difference in the amount of surface deformation.

Model for Formation of Wear Particle

The results of the copper and ruby rider experiments indicate that adhesion plays a significant role in the generation of the fracture cracks shown in figures 3, 4, 7, and 8. The cracks developed with the copper rider but not with the ruby.

It is worthwhile considering just how these cracks might form, and once formed, the role they play in the generation of adhesive wear particles. This may best be accomplished with the aid of a schematic representation (fig. 11) of what is believed to occur on the copper crystal surface with sliding.

Initially, adhesion of copper to copper occurs through the surface films. The applied load is sufficiently high such that the shear stress in the grains of the bricrystal is exceeded, giving rise to slip. As sliding commences, plastic deformation of the copper occurs with the tangential motion. This deformation is not homogeneous, but occurs by slip band formation. Because of the large localized plastic strains in the slip bands of the asperity contact zones, compared with the surrounding matrix, the slip band region could be treated as a temporarily viscous inclusion in an elastic matrix. This freely slipping region would be expected to have a high shear stress concentration at its leading edge, which can account for localized plastic deformation. If this free slipping is blocked, then very large tensile stresses can develop with tangential motion. These stresses can exceed the cohesive strength along the slip band and result in the formation of a crack. This is indicated in figure 11. The basic concept of fracture initiated at slip

bands is well established (ref. 9). The mechanism was proposed by Zener in his model of fracture in metals (ref. 10).

The interesting aspect of the Zener model is that it was originally proposed for brittle fracture in metals at low temperatures. Zener indicated that localized plastic deformations could occur at brittle conditions to give rise to fracture cracks. These same localized deformations occur in sliding at asperity contacts. Thus, an analogous situation exists. The only difference is that in sliding on copper at room temperature, the matrix is not brittle. The high local strain in sliding may account for the observance of fracture cracks in sliding.

The copper on the side of the crack nearest the surface is peeled up because of adhesion and tangential motion as indicated in figure 11. This material then projects above the plane of the surface. Subsequent passes can result in fracture of the material above the plane of the surface, thus generating a wear particle.

The angle θ of figure 11 is the angle formed between the grain surface and the slip band. If the length of the crack is kept constant and the length of the material peeled is the same, then for the generation of a single wear particle the larger the angle θ the greater will be the size of the wear particle generated upon fracture.

CONCLUSIONS

Based on the results obtained in this investigation with copper and ruby riders sliding on a copper bicrystal in air, the following conclusions are drawn:

1. The friction coefficient, adhesive behavior, and width of the surface track were markedly different on the two adjacent grains. The (111) grain gave a lower friction coefficient, less evidence of adhesion, and a narrower surface track than did the (210) grain.

2. With a copper rider sliding on the bicrystal surface, friction was different in the grain boundary region.

3. The formation of surface cracks was observed in both copper grains with a single pass of the copper rider across the surface. These cracks appear to develop along slip bands. They are the precursors for the formation of adhesive wear particles.

4. Fracture cracks were not observed with a ruby rider when adhesion is negligible compared with copper, which indicates that adhesion plays an important role in the development of these cracks.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, January 30, 1973,
            502-01.

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Drive motor for moving crystals

Strain-gage assembly

Load

Copper or ruby rider

Copper bicrystal

2.5 cm
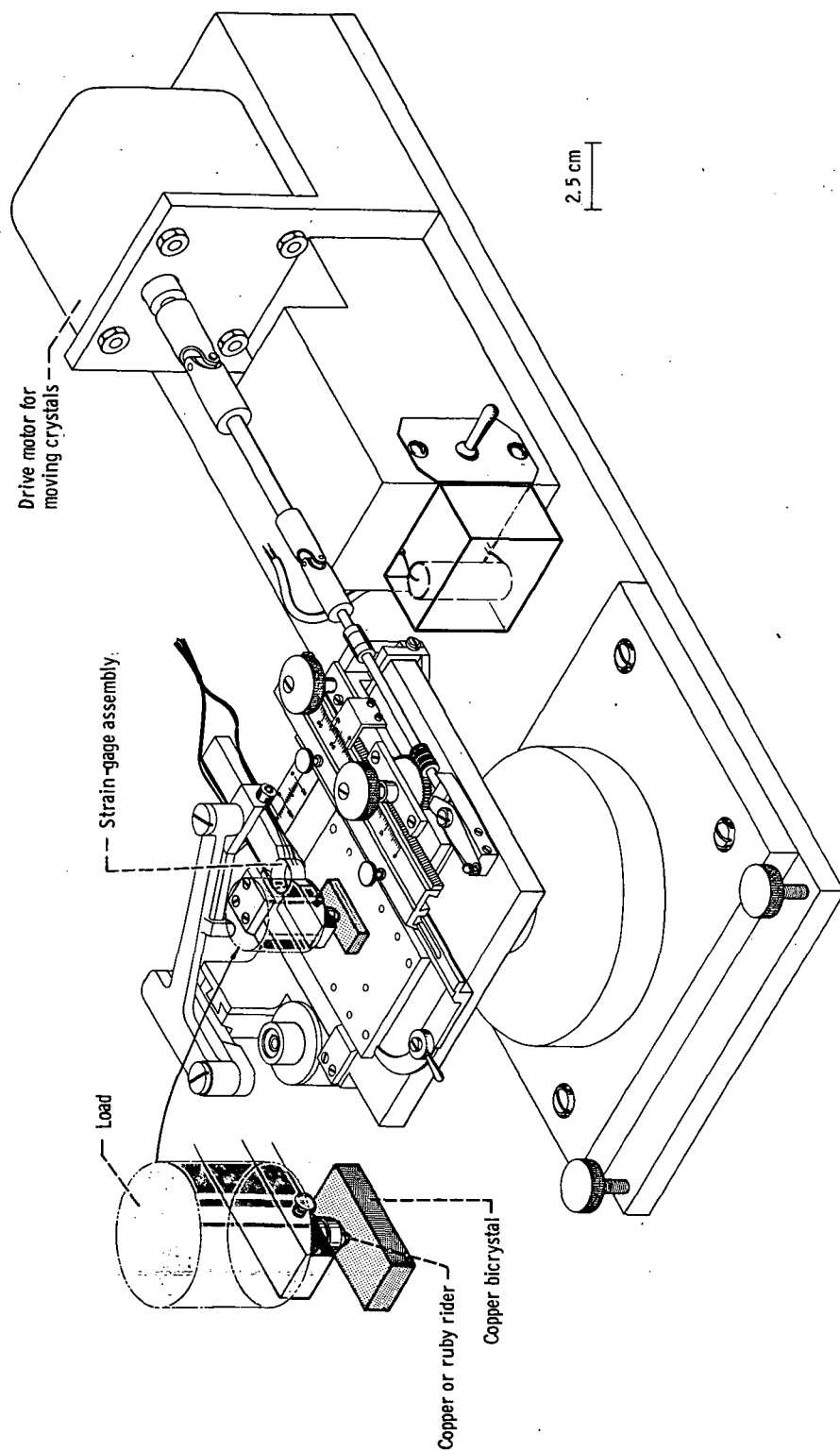
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Figure 1. – Sliding friction apparatus.

(a) From (210) to (111).

(b) From (111) to (210).
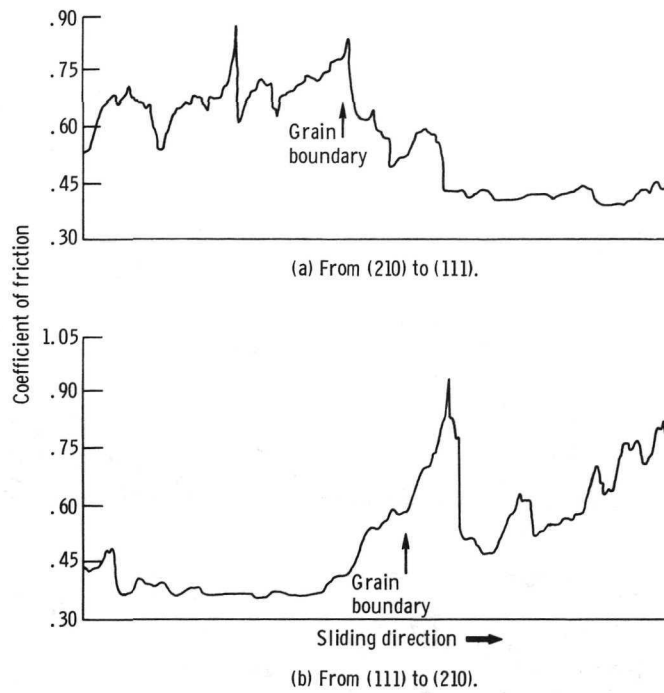
Figure 2. - Recorder tracings of friction force for copper slider sliding across grain boundary on copper bicrystal. Load, 100 grams; sliding speed, 1.4 millimeters per minute.
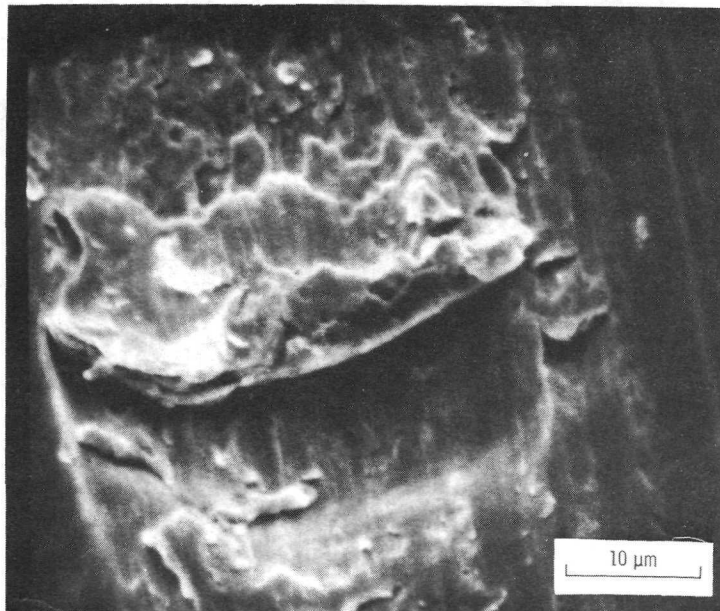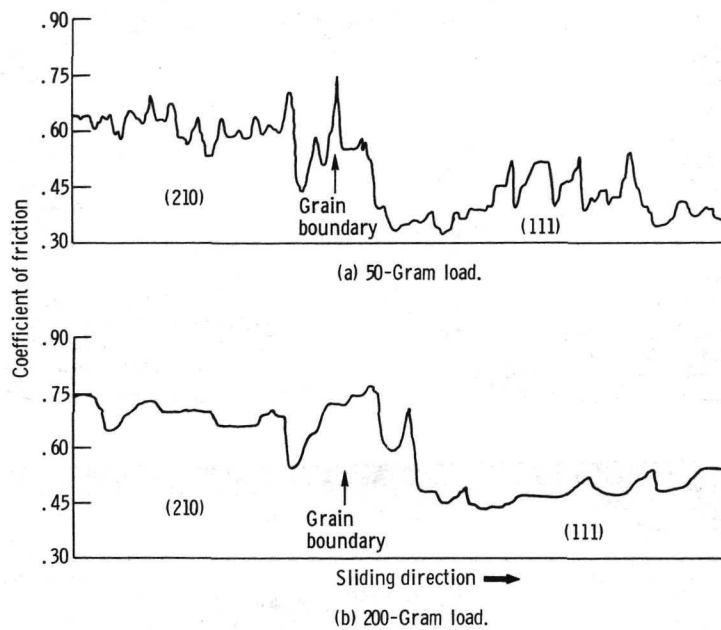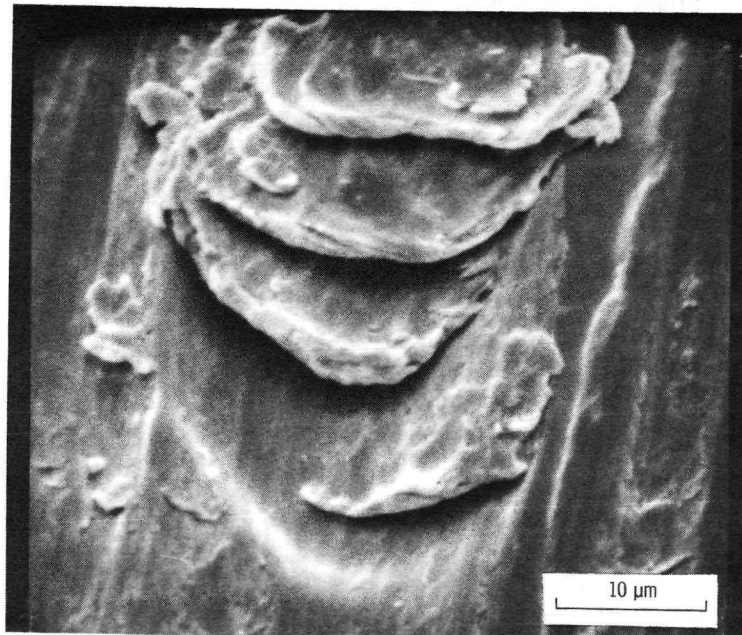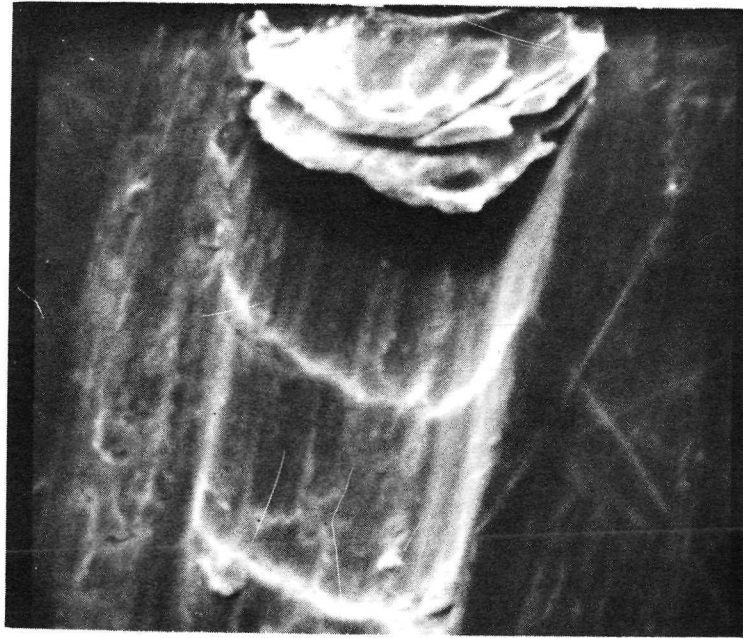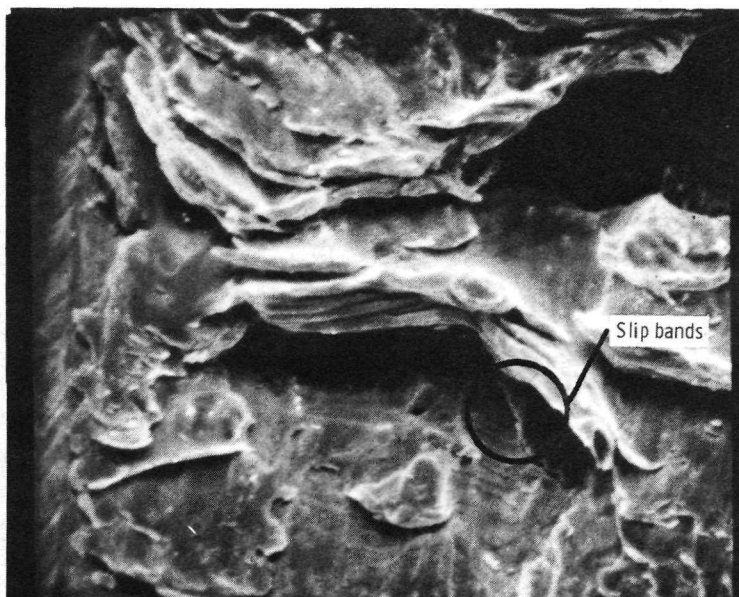
(a) (111) grain.

100 μm
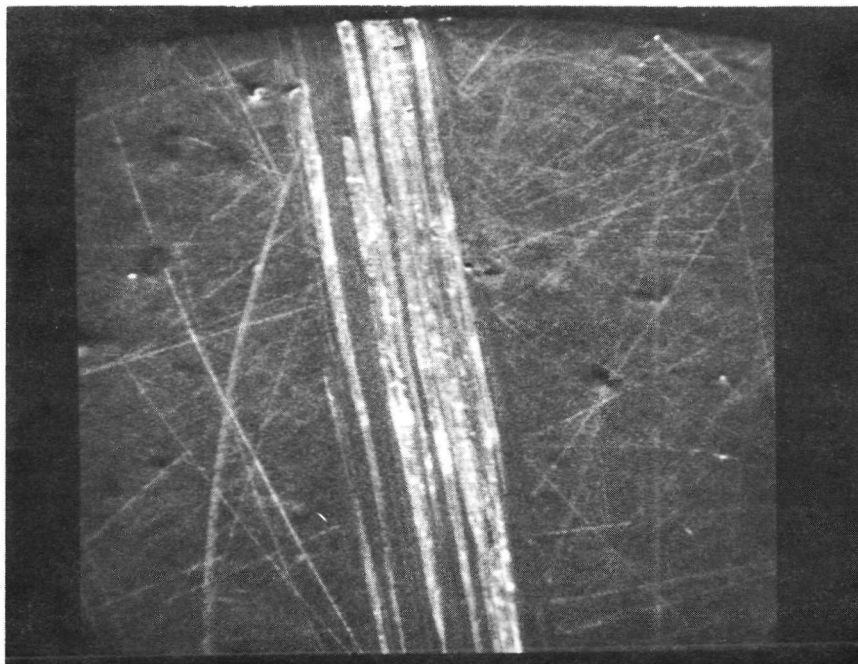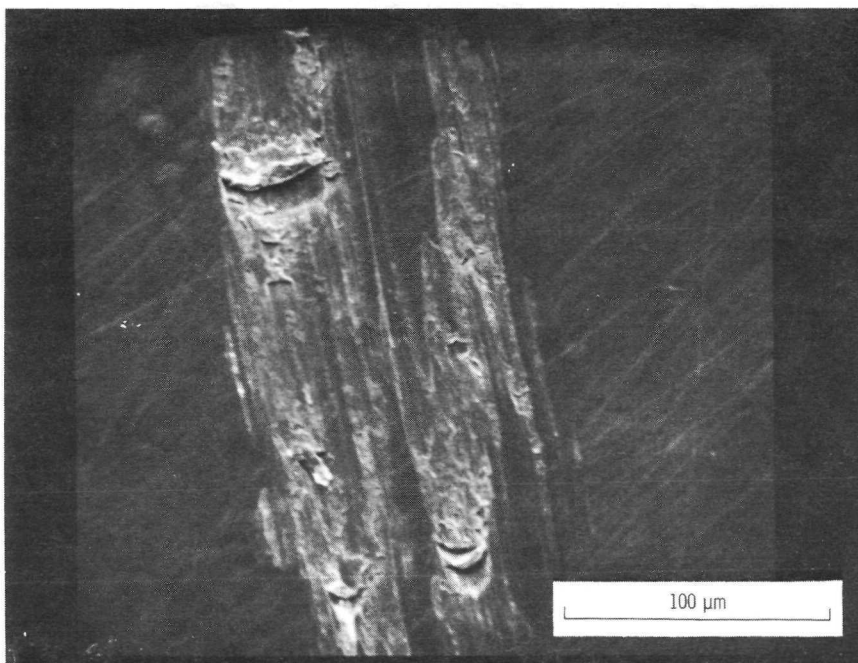
(b) (210) grain.

Figure 3. - Wear tracks on bicrystal grains. Copper slider; load, 100 grams; sliding speed, 1.4 millimeters per minute.

(a) (111) grain.

10 µm
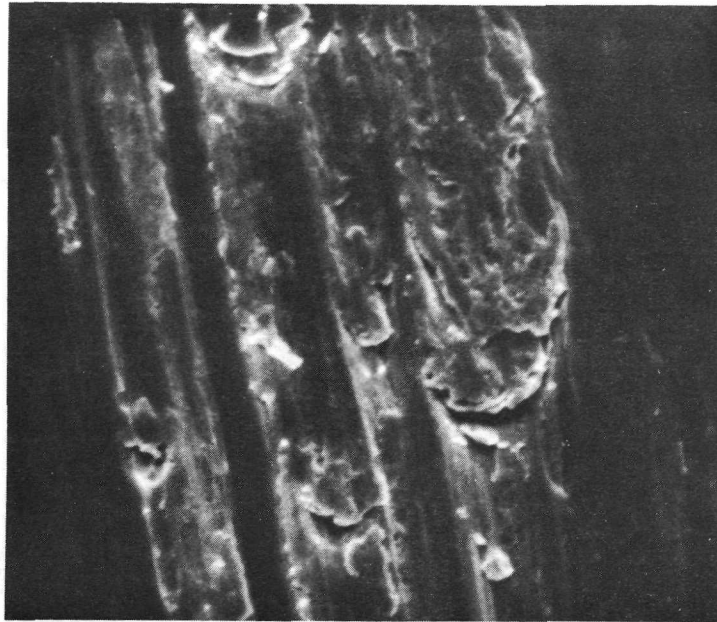
(b) (210) grain.

Figure 4. - Wear tracks on bicrystal grains. Copper slider; load, 100 grams; sliding speed, 1.4 millimeters per minute.
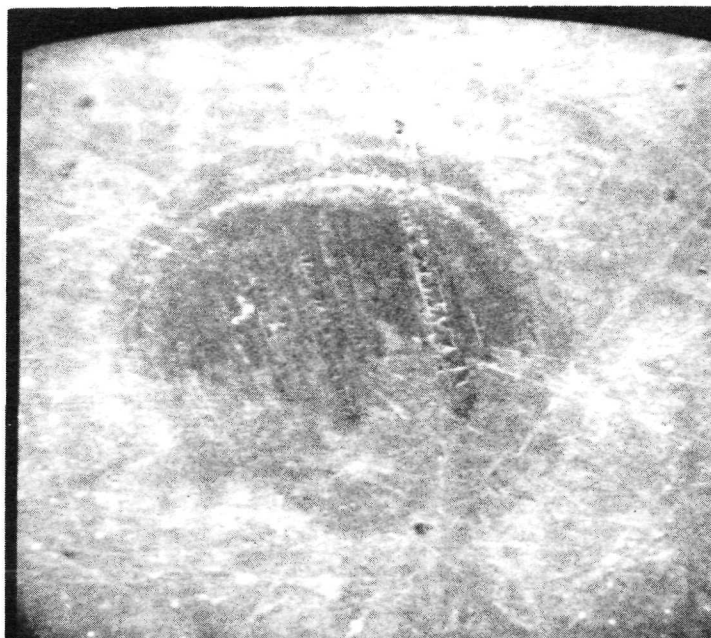
(a) Run on (111) grain only.

10 μm
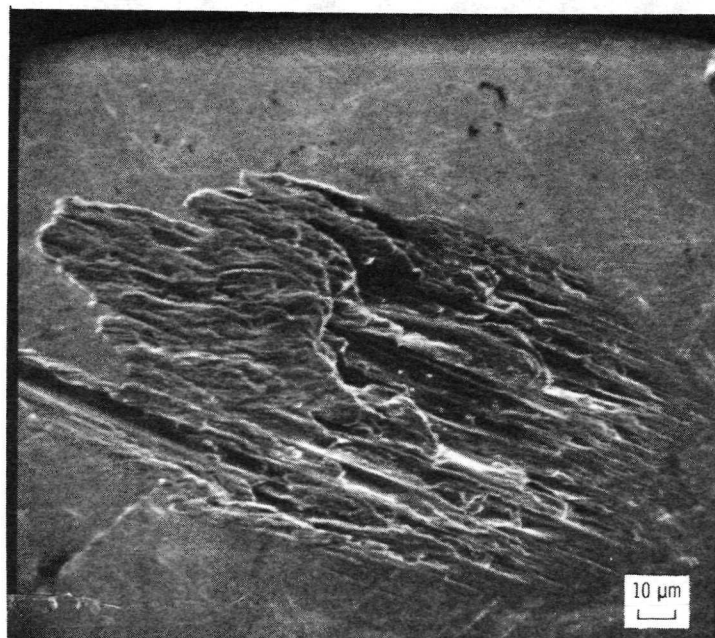
(b) Run on (210) grain only.

Figure 5. - Polycrystalline copper rider scars after sliding equal distances on bicrystal grains. Load, 100 grams.

Figure 6. – Actual recorder tracings of friction force for copper slider sliding across grain boundary on copper bicrystal. Sliding speed, 1.4 millimeters per minute.
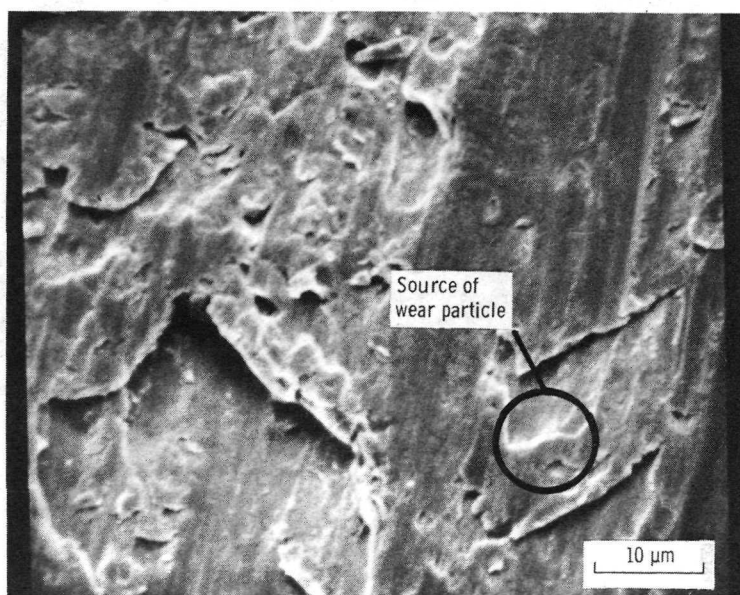
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Figure 7. – Areas of wear track on (210) grain, copper slider. Load, 50 grams per minute, sliding speed, 1.4 millimeters per minute.
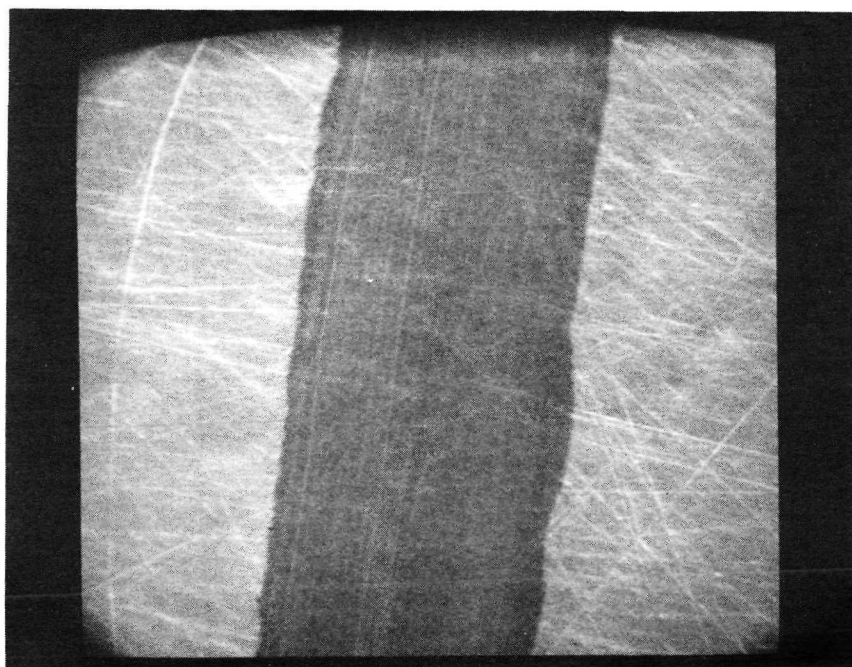
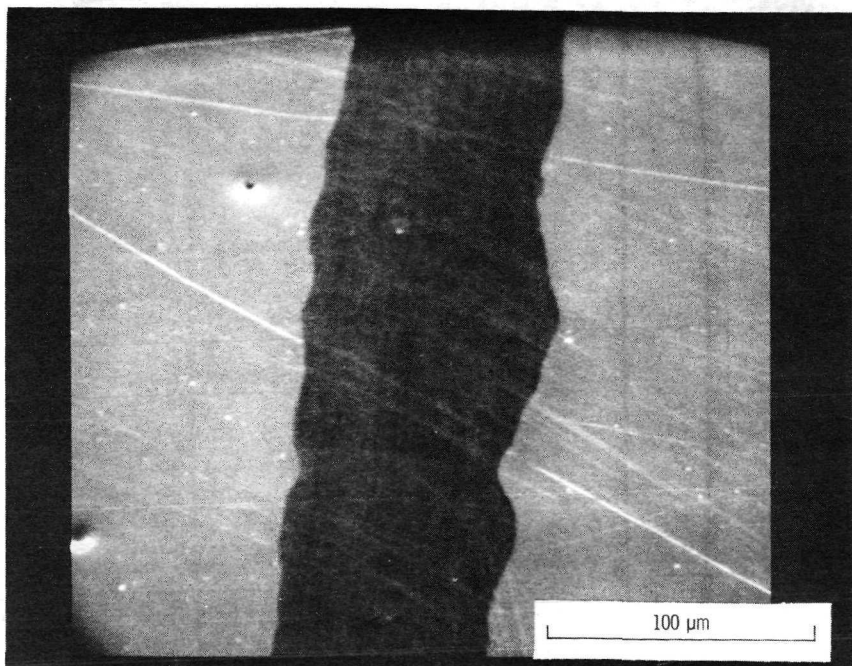(a) Generation of slip bands in wear track.

(b) Generation of wear particles.

Figure 8. - Wear track on (210) grain. Copper slider; load, 200 grams; sliding speed, 1.4 millimeters per minute.

(a) (111) grain.

100 μm

(b) (210) grain.

Figure 9. – Wear tracks on bicrystal grains.   Sapphire slider; load, 100 grams; sliding speed 1.4 millimeters per minute.

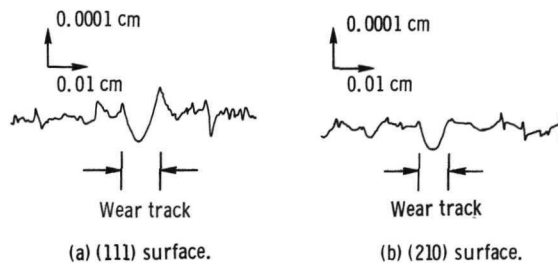16

(a) (111) surface.   (b) (210) surface.

Figure 10. - Surface profile tracings across wear tracks on both grains of bicrystal run against sapphire slider. Load, 100 grams; sliding speed, 1.4 millimeters per minute.
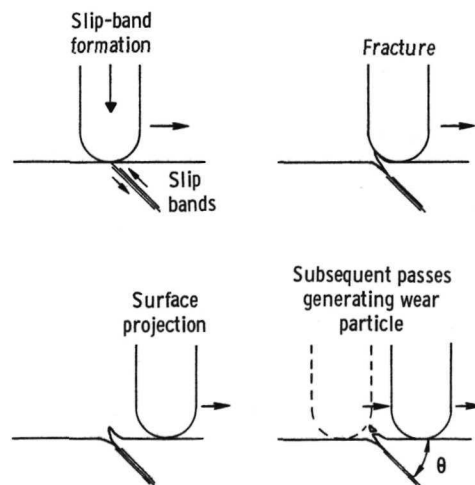

Figure 11. - Origin of surface fracture and formation of wear particle.

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